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MEMORANDUM
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MARCH 1962

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RULES FOR PLANNED REPLACEMENT OF AIRCRAFT AND MISSILE PARTS

M. Kamins

PREPARED FOR:
UNITED STATES AIR FORCE PROJECT RAND

The RAND Corporation
SANTA MONICA • CALIFORNIA

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MEMORANDUM
RM-2810-PR ~~(ABRIDGED)~~
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RULES FOR PLANNED REPLACEMENT OF AIRCRAFT AND MISSILE PARTS

M. Kamins

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PREFACE

This Project RAND Memorandum is part of a long-term study of maintenance policies and their effect on Air Force capabilities and costs. It specifically examines the interactions between planned replacement -- a form of preventive maintenance -- and the factors of reliability, availability, and cost.

The study was initiated when it became apparent that better application of the principles of planned replacement could result in worthwhile reductions in maintenance cost and weapon-system downtime.

This Memorandum is an abbreviated version of M. Kamins and J. J. McCall, Jr., Rules for Planned Replacement of Aircraft and Missile Parts, The RAND Corporation, Research Memorandum RM-2810-PR, November 1961. It was condensed for presentation as a briefing during January and February, 1962, to interested groups at SBAMA, Ballistic Systems Division, First Missile Division, the Directorate of Maintenance at Hq USAF, Air Force Logistics Command, and a small number of groups outside the Air Force.

A related work which the reader may also find useful is M. Kamins, Determining Checkout Intervals for Systems Subject to Random Failures, The RAND Corporation, Research Memorandum RM-2578, June 15, 1960.

Letter on file

A

SUMMARY*

The appropriate replacement policy for a part depends on its failure characteristics and the relative costs of an in-service failure and of a planned replacement (replacement before failure). For planned replacement to be worthwhile, the part must display a wearout characteristic (a failure rate increasing with time); and the cost of an in-service failure must be greater than the cost of a planned replacement.

Failure-data analysis has shown that many aircraft and missile parts fail exponentially; that is, they have a constant failure rate. In these cases, a new part is no better than a used but serviceable part of any age. The optimum replacement policy for these parts -- optimum in the sense of minimizing expected cost per unit time -- is a simple one: Never plan to replace before failure, regardless of how expensive or inconvenient an in-service failure becomes.

On the other hand, analysis of failure data has also uncovered many parts with non-exponential failure characteristics. Substantial numbers of these parts exhibit an increasing failure rate over time. In this situation the age at which the part should be replaced depends on the relative cost of an in-service failure. In general, for a given aging effect, the higher the relative cost of an in-service failure, the shorter should be the planned-replacement interval. Similarly, for a given in-service failure cost, the more severe the aging effect the shorter the replacement interval.

In this study, specific replacement policies were obtained for parts which fail according to one of four continuous probability distributions.

*This Research Memorandum is an abbreviated version of M. Kamins and J. J. McCall, Jr., Rules for Planned Replacement of Aircraft and Missile Parts, The RAND Corporation, Research Memorandum RM-2810-PR, November, 1961.

An analysis of commercial-airline and Air Force failure data indicates that the times-of-failure of many aircraft parts fit one of these distributions.

Replacement policies based on discrete probability distributions were also examined. A computational routine was developed to determine the optimum planned-replacement interval for parts whose failure characteristics are best described by these discrete distributions.

PLANNED REPLACEMENT

The notion of planned replacement, or replacement of an item before it fails, is undoubtedly familiar to you. Replacement or overhaul at some specific age is mandatory for a wide variety of aircraft parts, notably engines and engine accessories. You may have other names for it -- scheduled maintenance, preventive maintenance, and the like. You are also very much aware of two of the objectives of such a policy: namely, safety and reliability. But if planned replacement can help achieve these desirable qualities, it can also save time and contribute to improved in-commission rates, lower costs, or some combination of these. The objective of this study was to learn some of the characteristics of this tool, planned replacement, in order to discover the factors that determine when and how it should be used for the most desirable results.

In reporting to you briefly on the results of this research, I'll first discuss the two conditions that are necessary before planned replacement is at least potentially worthwhile. Then I'll consider these two conditions further, to show how likely they are to occur in practice, and how to quantify them. Next, I'll describe a sort of all-purpose goal that should allow you to use a single method to give you just the emphasis you want, whether it's reliability, cost, or any combination. Before winding up, I'll talk about some of the difficulties you might run into when you try to use these analytical tools.

Now, what are the two conditions that are necessary to make planned replacement worthwhile?

First, there must be some advantage to avoiding an unexpected failure or a failure in service. The planned or scheduled replacement of a unit,

be it a system, subsystem, component, or almost anything else, must "cost" less, in some sense, than an emergency, or unexpected, or unscheduled replacement. This is intuitively reasonable; if you make a planned replacement when there is no advantage in avoiding a failure, you throw away some unused life and get nothing in return.

The second condition is less intuitive and generally less easy to understand. Planned replacement must reduce the chance that a failure will occur. The new part must be better, or more reliable, than the part being replaced. In order for this to be so, the part in question must display a wearout characteristic. Of course, we all know that most things wear out eventually; that's not what I mean. By wearout, I mean an increasing failure rate or a decreasing reliability with the passage of time. The failure rate is defined as the probability that a unit which is good at some specific point in time will fail before one additional unit of time has elapsed. Notice that this is just the opposite of the reliability, since reliability is the probability that the unit will survive the next time period. So our second condition is equivalent to a decreasing reliability.

Figure 1 is a plot made from actual field experience, showing the failure rate as a function of time since major overhaul for an engine accessory used by one of the major airlines. We call this a bathtub curve, for obvious reasons. Notice that during the first 600 hours of operation, the failure rate decreases by about half -- a phenomenon commonly called "infant mortality" or "burn-in" in reliability circles. During the next 800 hours of operation, the failure rate is essentially constant; failures here are usually referred to as "random," and are the ones most commonly

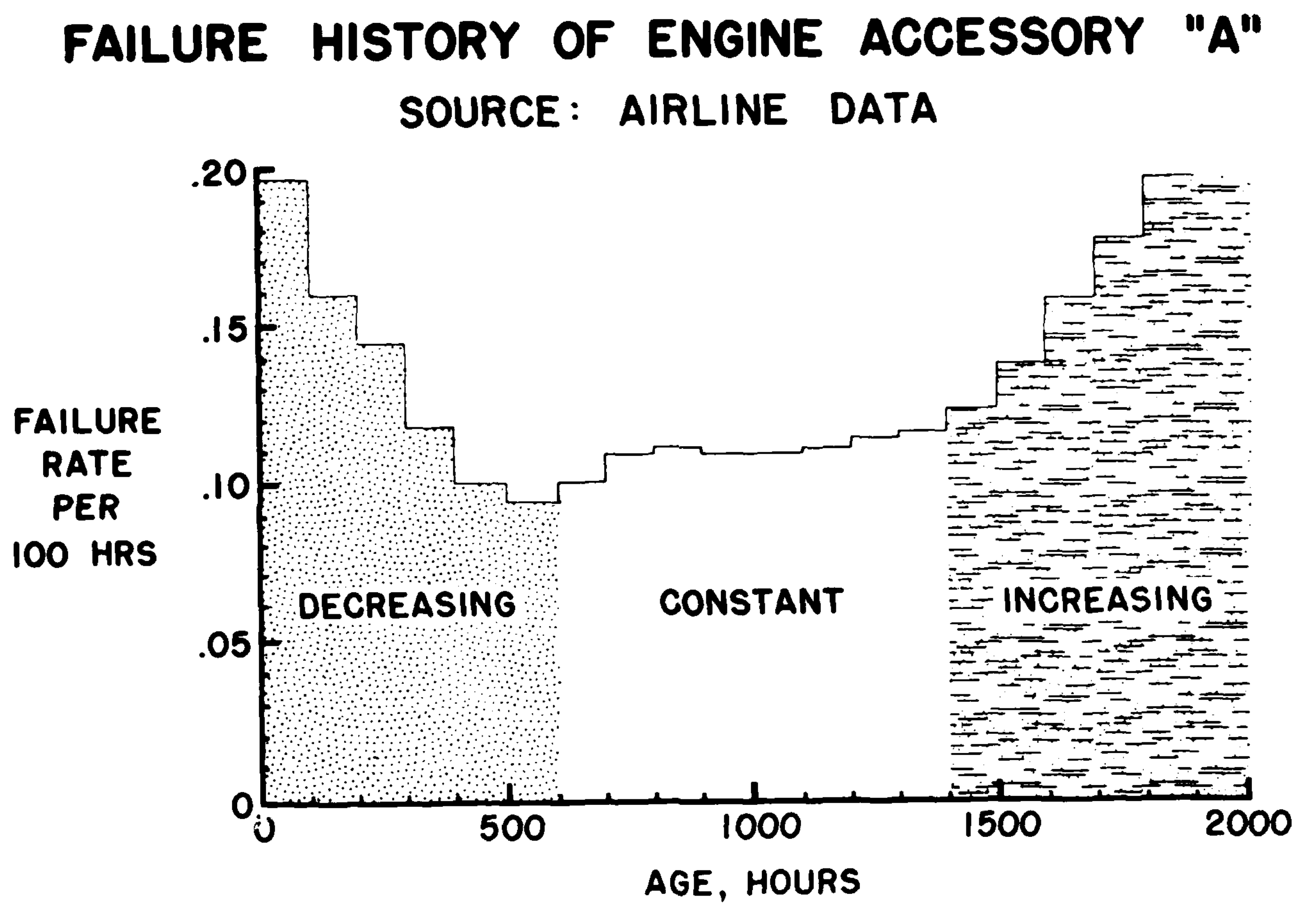
FAILURE HISTORY OF ENGINE ACCESSORY "A"
SOURCE: AIRLINE DATA
FAILURE RATE PER 100 HRS
.20
.15
.10
.05
0
0
500
1000
1500
2000
AGE, HOURS
DECREASING
CONSTANT
INCREASING

Fig. 1

assumed in reliability studies. They have also been called "exponential," "chance," "accidental," or "Poisson" failures.* After the 140-hour mark, the failure rate starts increasing again, and we call this the "wearout region."

Now let's consider using planned replacement at 500 hours for this accessory. The new one we install will have about a 20-per-cent chance of failure during the first 100 hours of operation. But if we had left the 500-hour survivor alone, it would only be half as likely to fail in the next 100 hours. Obviously, planned replacement is extremely undesirable at this particular time.

Now suppose we consider planned replacement at 1000 hours. The same thing happens. Suppose further that we get rid of the burn-in phenomenon by improving environmental testing and quality control procedures, so that our curve flattens out at the left end (Fig. 2). The thousand-hour part is still no more likely to fail in the next 100 hours than is the new one. If we used planned replacement here, we'd be throwing away a substantial amount of unused life, and getting nothing in return. Planned replacement is not warranted when random failures are involved, meaning specifically a constant failure rate; but unfortunately, this is a fairly common practice today, both in the Air Force and in commercial aviation.

By now it should be evident that as time passes, and we move to the right on this diagram, we'll soon find a place where planned replacement may be worthwhile, but it can't happen before we get to the wearout region, where the failure rate is increasing. Later, we'll see it's at least 1540 hours, and is usually even more.

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*See M. Kamins, Determining Checkout Intervals for Systems Subject to Random Failures, The RAND Corporation, Research Memorandum RM-2578, June 15, 1960.

MODIFIED FAILURE HISTORY OF ENGINE ACCESSORY "A"

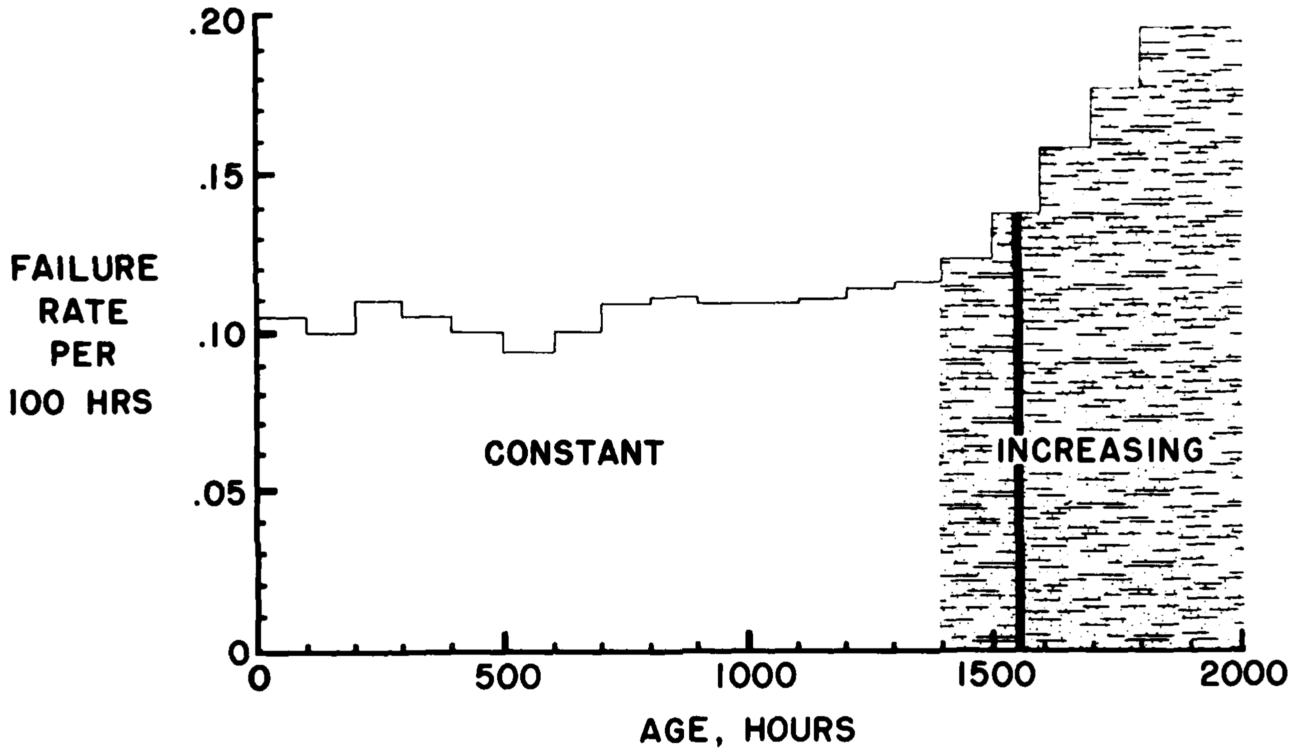

Fig. 2

So we need two things: an increasing failure rate, and some penalty for a failure-in-service. Then we can forego some useful life and get in return a reduced probability of something undesirable happening. When we quantify this trade-off, we can get the most out of planned replacement.

How important is a failure-in-service? Keeping in mind the increasing failure rate, it's evident that the more important a failure is, the earlier we'll want to make a planned replacement. This means that if we over-estimate its importance, we'll replace too early, and if we underestimate, we'll replace too late for best results. In some cases, an explicit estimate of the cost of a failure-in-service may be inappropriate or totally unavailable. This is generally true when a failure-in-service would degrade flight safety and endanger human life. This means that safety-of-flight items in aircraft carrying humans, either as crew or passengers, are poor candidates for application of certain of the rules developed here, though not all of them.

However, with the current emphasis on extensive and thorough redundancy in vital systems for both military and commercial aircraft, situations dominated by flight-safety considerations rarely occur. Ordinarily the failure of an aircraft part causes nothing worse than a delayed flight, an unfulfilled mission, an expedited repair action, or comparable occurrences whose importance can usually be defined quantitatively. In an unmanned aircraft or missile, where redundancy is the exception rather than the rule, the potential loss of the flight vehicle or support equipment (or both) may be real possibilities whose costs should be weighed in any replacement-policy action.

In the absence of safety considerations for flight personnel or the catastrophic-damage potential, the cost of a replacement action, scheduled

or unscheduled, depends on (1) the time during which the aircraft or missile is out of commission, either awaiting a replacement action or having the action performed; and (2) the resources required to accomplish the replacement action. Let us examine each of these in turn, noting the relation between a scheduled and unscheduled action.

The total elapsed time between the demand for a replacement action and its completion is a period of no operational capability. The value of this downtime is the value of the operational availability which would have existed had no replacement action been required. There are several reasons for expecting this loss of value to be higher for an unscheduled replacement than for a scheduled one. Because of the unexpectedness of an unscheduled replacement, the reaction to a demand for service is seldom immediate. On the contrary, long periods are frequently spent awaiting service. On the other hand, by the very nature of a scheduled replacement, this waiting time can be reduced substantially, and the system is typically available right up to the time work actually begins. Another reason for expecting unscheduled downtime to last longer is that the actual replacement time is often greater for an in-service failure than for a planned replacement. Not only is it sometimes more difficult to replace a failed part than to replace an unfailed one, but the failure of one part frequently causes damage to other parts. Then too, it may take some time to diagnose location of the failure. Finally, the value per unit time of the lost capability during an unscheduled action often exceeds the same measure for a scheduled action. For example, if an unexpected defect turns up in an aircraft or missile on an alert commitment, finding a substitute in a hurry may mess up somebody's schedule for maintenance or training.

The second factor affecting the cost of a replacement action is the amount of resources required to perform the action. Usually more resources will be needed for an unscheduled replacement, for three reasons: (1) The replacement of a failed part is usually a more complex operation than is a planned replacement, and the salvage value of a failed part may be considerably less than that of an unfailed part. (2) Additional resources may be needed to repair parts whose damage was induced by the in-service failure. (3) Finally, when a replacement is unscheduled, it is often necessary to transport maintenance resources to the failed system instead of bringing the system to the resources. A planned replacement avoids the high cost of these expedited actions.

For these reasons we should expect it to cost more to repair an in-service failure than to make a planned replacement, under the most general circumstances of both military and commercial operations.

But no matter how detrimental a failure in service may be, planned replacement offers no help unless the part in question has an increasing failure rate. How can you tell if it has? In principle, it isn't very difficult to use what's called the actuarial method, the same thing life insurance actuaries use to quantify human mortality. You need failure data -- information on which parts failed, and at what age. Then, to get the failure rate for a given interval, you need only divide the number of failures which occurred in the interval by the number of parts which operated in the interval. For example (Fig. 3), the engine accessory I mentioned previously had a total of 15 failures in the interval between 200 and 300 flying-hours, while the number operating in the interval was 103.52. This latter quantity isn't a whole number, because a part which failed halfway

THE ACTUARIAL METHOD

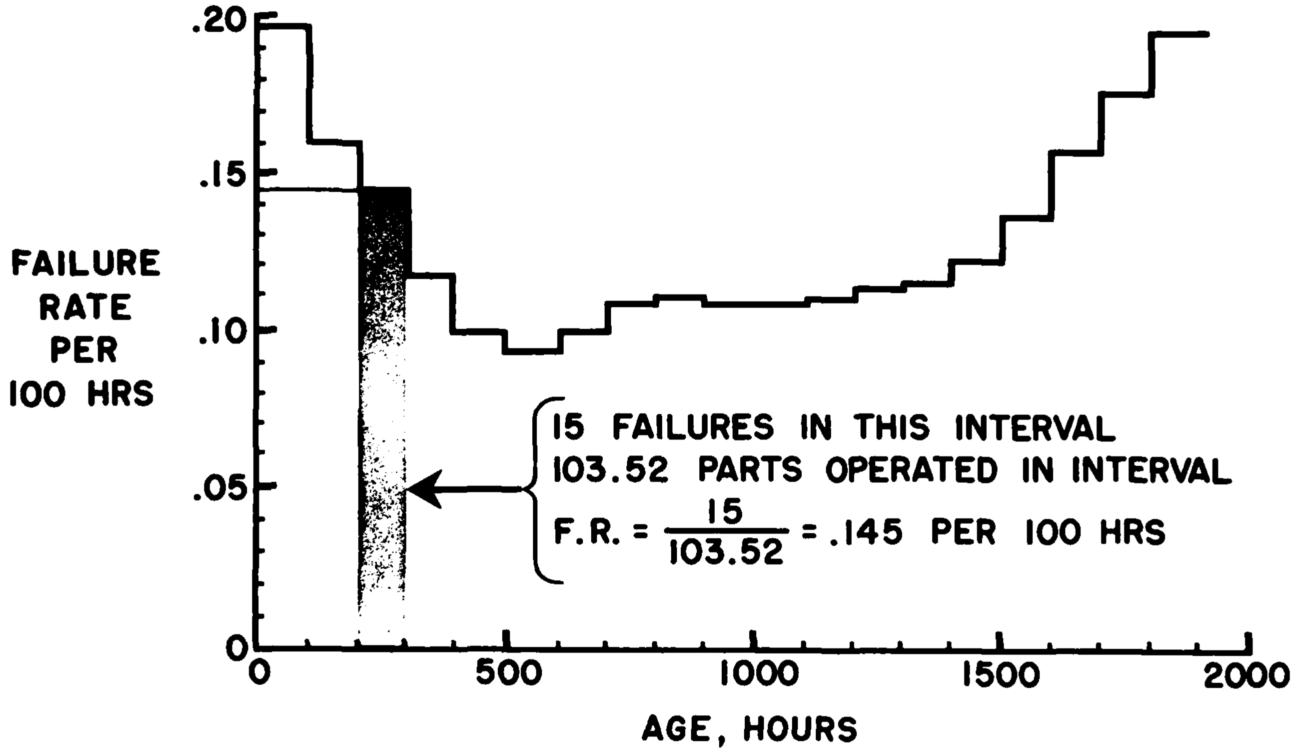

Fig. 3

through the interval, let us say, contributes only that particular fraction to the total. We find that the failure rate of this part in the interval from 200 to 300 flying-hours is 0.145. This method of computation is explained in considerable detail in Air Force Technical Order T.O. 00-25-128, "Procedures for Determining Aircraft Engine Failure Rates, Actuarial Engine Life, and Forecasting Monthly Engine Changes by the Actuarial Method." This T.O. also contains sixty pages of tabulated failure rates which cover every engine used by the Air Force. Similar tables are available for propellers.

To get some information on the failure characteristics of aircraft parts other than engines and propellers, we went to the commercial airlines, which apply the actuarial method to hundreds of parts. We also studied several reports concerning failure experience, including the granddaddy of them all, a study done at RAND ten years ago by D. J. Davis.*

As we expected, we found some things which were very interesting from the standpoint of planned replacement. For example, when we tried to categorize the failure characteristics, the largest single category was a familiar one -- the random distribution of failures. This distribution seems to represent the failure pattern of a wide variety of devices, primarily electronic, but including some mechanical and electromechanical ones as well. This is extremely significant relative to planned replacement. A random distribution means a constant failure rate, and as we just saw, a part with this characteristic should not be replaced before failure.

We found another, and somewhat smaller, group of parts whose failure characteristics could be described by some of the better-known probability distributions of mathematical statistics. One example (Fig. 4) is an engine whose failures have what's called a Normal distribution, one which occurs

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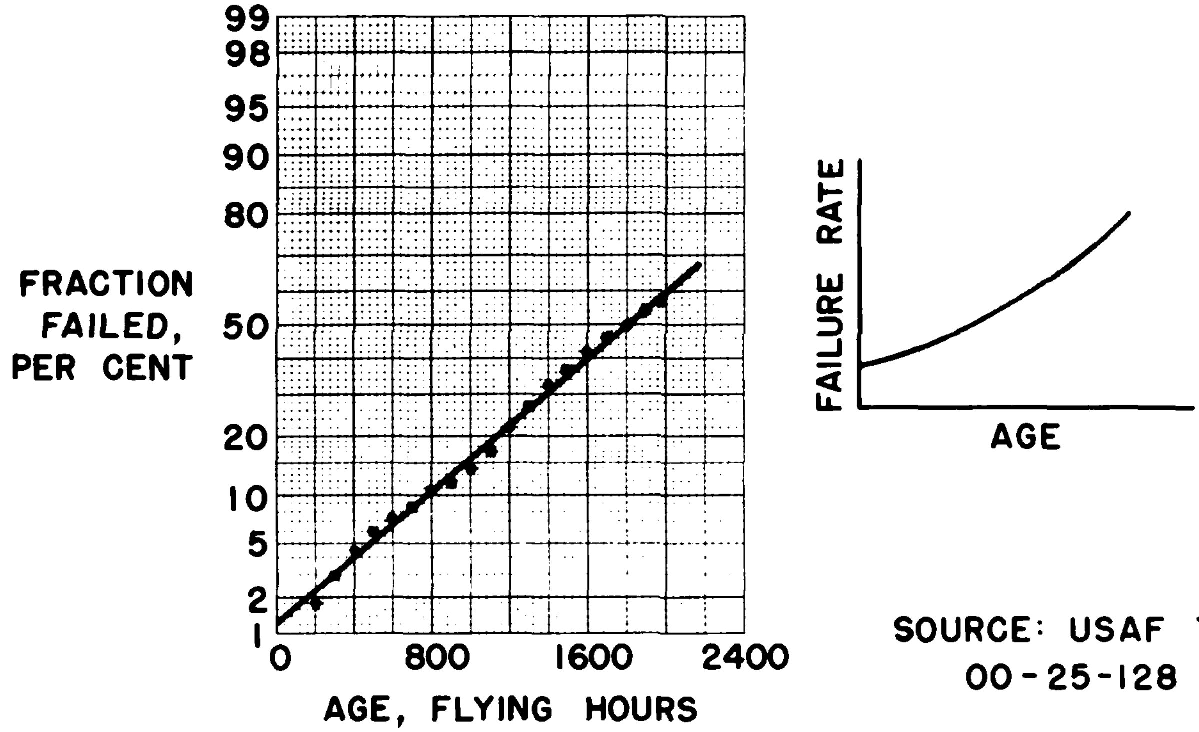
*D. J. Davis, "An Analysis of Some Failure Data," J. Amer. Stat. Ass., Vol. 47, No. 258, June, 1952, pp. 113-150. Or see idem, The RAND Corporation, Paper P-183, February 12, 1952.

FRACTION FAILED VS AGE

J57F-59 AND J57P-59 ENGINES



SOURCE: USAF T.O.
00-25-128

Fig. 4

frequently in nature. This is a Normal probability grid. The vertical or "fraction failed" axis in Fig. 4 is divided so that the time-failure history for a part with a Normal distribution of failures is a straight line under most circumstances. This distribution is pertinent to planned replacement, since it has an increasing failure rate.

In Fig. 5 we have a propeller whose failures follow a Weibull distribution, named after the Swedish university professor who first suggested its usefulness in reliability work. As you may have guessed, this is called a Weibull Probability Grid. Both the vertical and horizontal scales on this chart are special. The random distribution is a member of this family, as shown by the upper line, and it also defines an interesting boundary for us. A failure-versus-time plot which is steeper than this has an increasing failure rate, like the propeller example. If it's less steep, the failure rate is decreasing.

In all, we found five types of so-called "continuous" distributions in our failure analyses. But even these five types did not cover all the parts we studied. Some could be described only by so-called "discrete" distributions, involving point-by-point or tabular representation of the failure rate; an example of this is the "bathtub" curve you saw earlier. Many of these had an increasing failure rate during at least part of their life history. No one particular distribution could describe the failures of any large class of parts, except for electronics, where random failures are all but universal.

In short, the failure analyses showed that while not all parts have an increasing failure rate, enough of them do to make planned replacement potentially worthwhile in many instances.

FRACTION FAILED VS FLYING AGE FOR A422 PROPELLER ON T-28

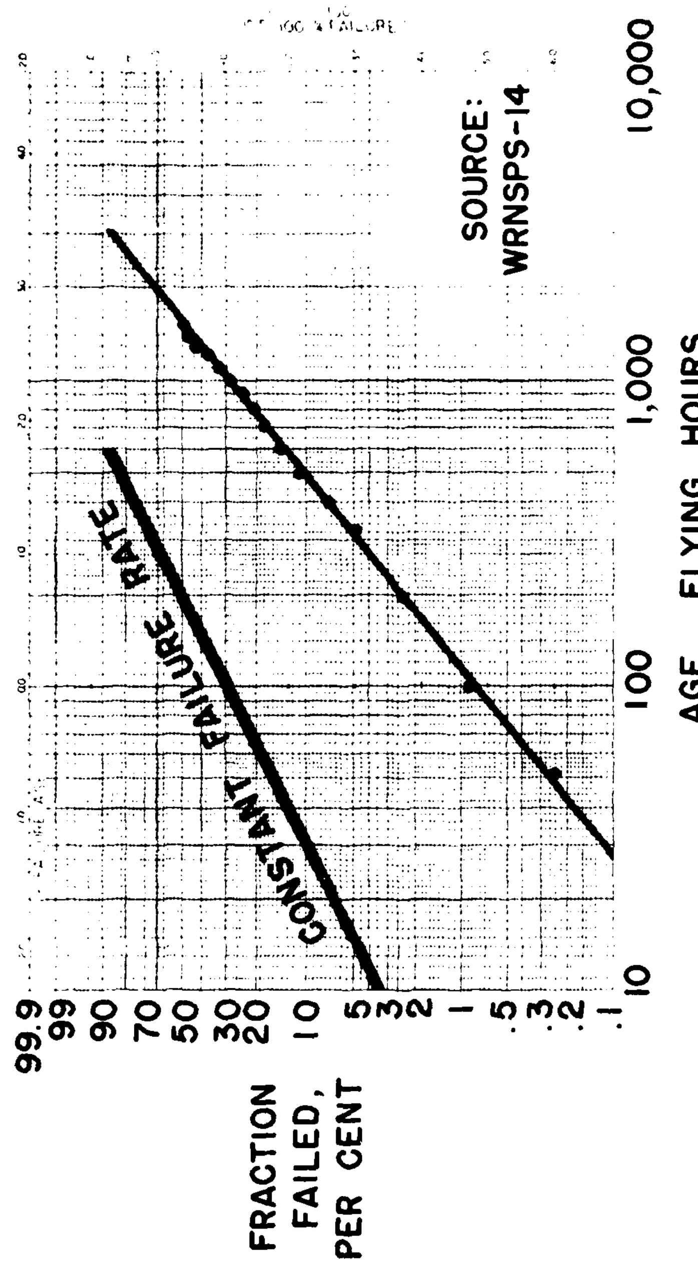


Fig. 5

Now why only "potentially" worthwhile? Earlier, I mentioned that getting the most out of planned replacement involves a tradeoff or compromise between the amount of useful service life we give up, and the reduced probability of a failure in service. Since it's always possible to give up more than we gain, we need some insurance against this happening.

The next step in the research study was to decide what was a desirable goal: how do you tell a good application of planned replacement from a bad one?

What are some plausible objectives for planned replacement generally? Minimum cost might be pretty attractive to a taxicab fleet operator, or even a commercial airline under special conditions. Reliability or safety might be appropriate in certain other cases. In the military, cost-effectiveness -- that is, the cost per ready weapon -- is often used as a measure of performance, though it isn't always the best one. As you can see, these objectives are generally incompatible with one another, and we'd like to wind up with some sort of versatile procedure which could be tailored to each of these and perhaps some others.

Two steps are required to achieve this versatility. The first is to express the various effects of failure and replacement in terms of a common quantity -- dollars, for example. In the Air Force it is sometimes difficult to do this with any reasonable accuracy. Even in other fields, such as airline operations, the detailed procedure takes more time than we can devote to it here; however, it can usually be done with an accuracy that's compatible with the rest of the process. Figure 6 is an example from an airline running an extensive overseas operation.

COST OF AN ENGINE FAILURE OVERSEAS

TRANSPORTATION	$ 14,000
LOSS OF REVENUE	5,600
ADDITIONAL HANDLING COST	1,400
TOTAL	$ 21,000

Fig. 6

Suppose an engine fails: the round-trip supply flight alone with a replacement engine costs about $14,000. Passengers must sometimes be transferred to another carrier; if so, the loss of revenue due to the delay is $5,600 (this assumes the transfer of 40 passengers on one delay out of four, at a residual fare of $560). The additional passenger-handling costs (food, lodging) for the three out of four delays not requiring transfer to another carrier is about $1,400, and the total is $21,000. Experience shows (Fig. 7) that only 40 per cent of the failures occur overseas, where these high costs hold, so that the average added cost is $8,400. At a home base, the whole replacement and overhaul process costs only $17,500, not much more than the transportation charge alone overseas.

Now let me do one more thing, using this same example involving costs. This is the second step which involves making the measure of the penalty dimensionless. We define the penalty for a failure in service as the ratio of $\frac{\text{Extra cost of a failure-in-service}}{\text{Cost of a planned replacement}}$. In our example, the normal replacement and overhaul cost is $17,500, so that the dimensionless penalty is 0.48. The dimensionless nature of this quantity is the second of the two keys to the versatility we want.

Now we have all the pieces; let's put them together. If we look for the minimum-cost replacement interval, we find it has this very simple characteristic, involving only four quantities (Fig. 8): failure rate times mean life minus fraction failed equals one over the dimensionless penalty for a failure in service.

To show what's happening here's a plot (Fig. 9) of cost per unit time for our old friend, Engine Accessory "A" against the planned replacement age, when the penalty for a failure in service is four -- a lot higher than

COST OF AN ENGINE FAILURE OVERSEAS (cont)

PERCENT OCCURRING OVERSEAS	40
AVERAGE COST OF A FAILURE = \$ 21,000 X .4 =	\$ 8,400
NORMAL COST OF OVERHAUL	\$ 17,500

$$\text{"PENALTY"} = \frac{\$\ 8{,}400}{\$\ 17{,}500} = 0.48 \ \text{(DIMENSIONLESS)}$$

Fig. 7

AT THE "MINIMUM COST" REPLACEMENT INTERVAL:

$$\text{FAILURE RATE} \times \text{MEAN LIFE} - \text{FRACTION FAILED} = \frac{1}{\text{PENALTY}}$$

Fig. 8

COST VS REPLACEMENT AGE

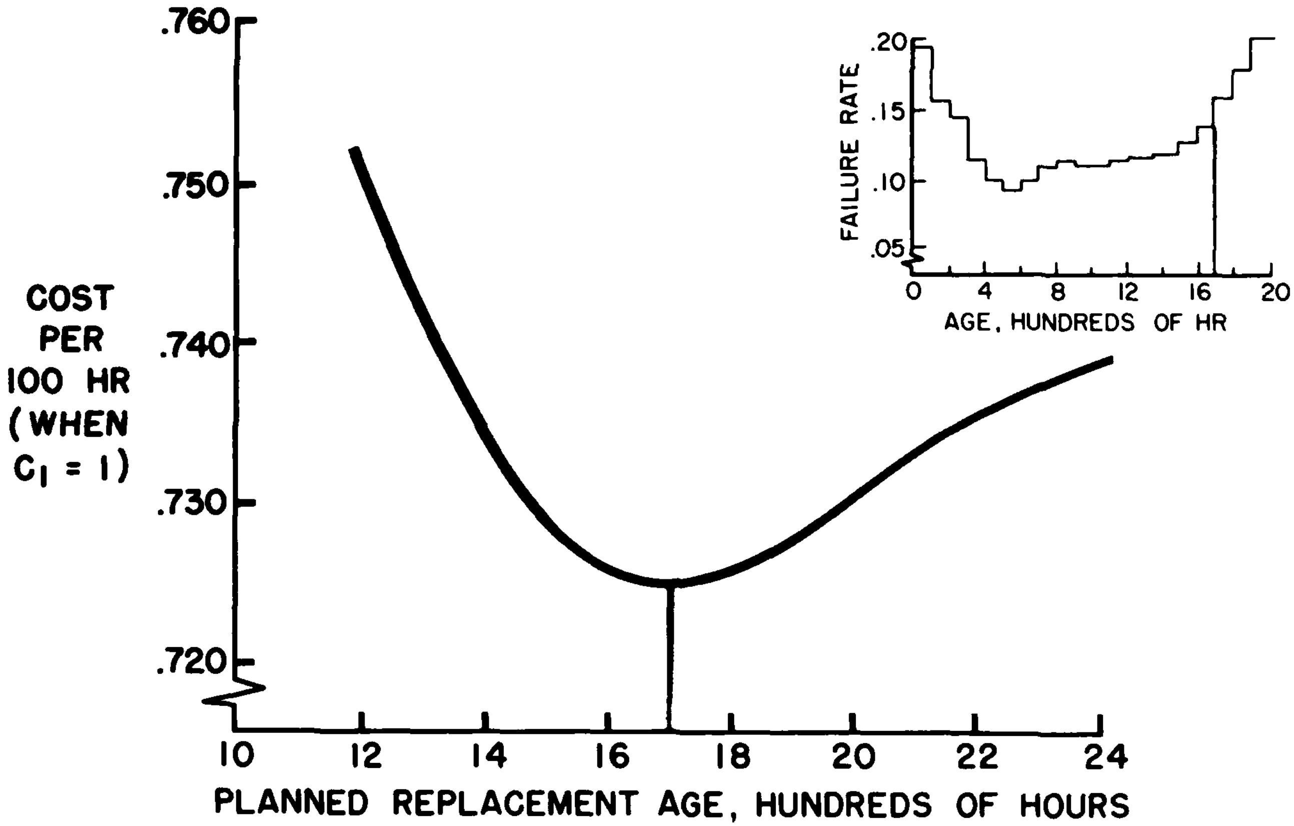


Fig. 9

it was for our overseas airline example. Our solution gives us the minimum-cost point at 17[illegible] flying-hours. If we institute planned replacement earlier or later than this age, costs are higher, substantially so on the early replacement side.

Here's the result (Fig. 10) of a machine computation for the same example, showing the best age for planned replacement as a function of the penalty for a failure in service. The point from the previous chart is shown as the large dot. As the penalty increases, we replace earlier. A while back I mentioned versatility, and here's an opportunity to show some of it. If our objective is maximum reliability instead of minimum cost, we simply make the penalty extremely severe, infinite if you wish, and find the appropriate replacement age, in this case 1540 hours.

Our results, then, consist primarily of a simple computing program to find the best replacement age for parts with discrete failure distributions, and empirical charts or nomograms (Fig. 11), to obtain the same results with one of four continuous distributions.

So far the road has been pretty smooth. Let's look at some of the bumps (Fig. 12). I mentioned earlier that it's possible to give away more in terms of unused service life than we get back in terms of fewer failures, and the mathematics of the solution doesn't prevent this from happening. Therefore, we have included in our results, for both continuous and discrete distributions, a measure of the savings, if any. These are gross savings, however. One should subtract from them the extra cost of administering a planned-replacement program, as opposed to a replace-at-failure-only policy. An example of such extra costs might be increased data-collection costs.

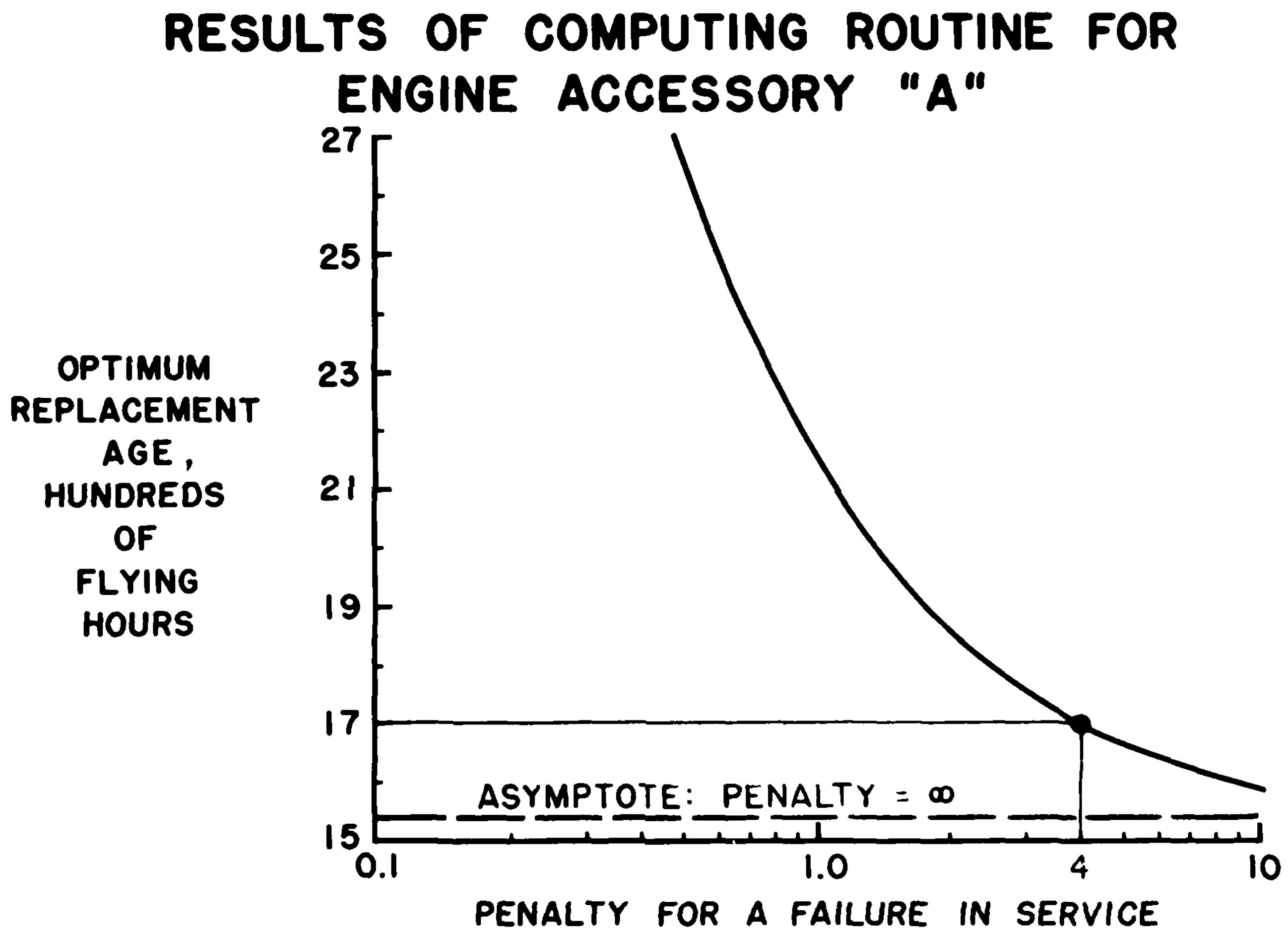

RESULTS OF COMPUTING ROUTINE FOR
ENGINE ACCESSORY "A"
OPTIMUM
REPLACEMENT
AGE,
HUNDREDS
OF
FLYING
HOURS
27
25
23
21
19
17
15
0.1
1.0
4
10
ASYMPTOTE: PENALTY = ∞
PENALTY FOR A FAILURE IN SERVICE

Fig. 10

NOMOGRAM FOR NORMAL DISTRIBUTION

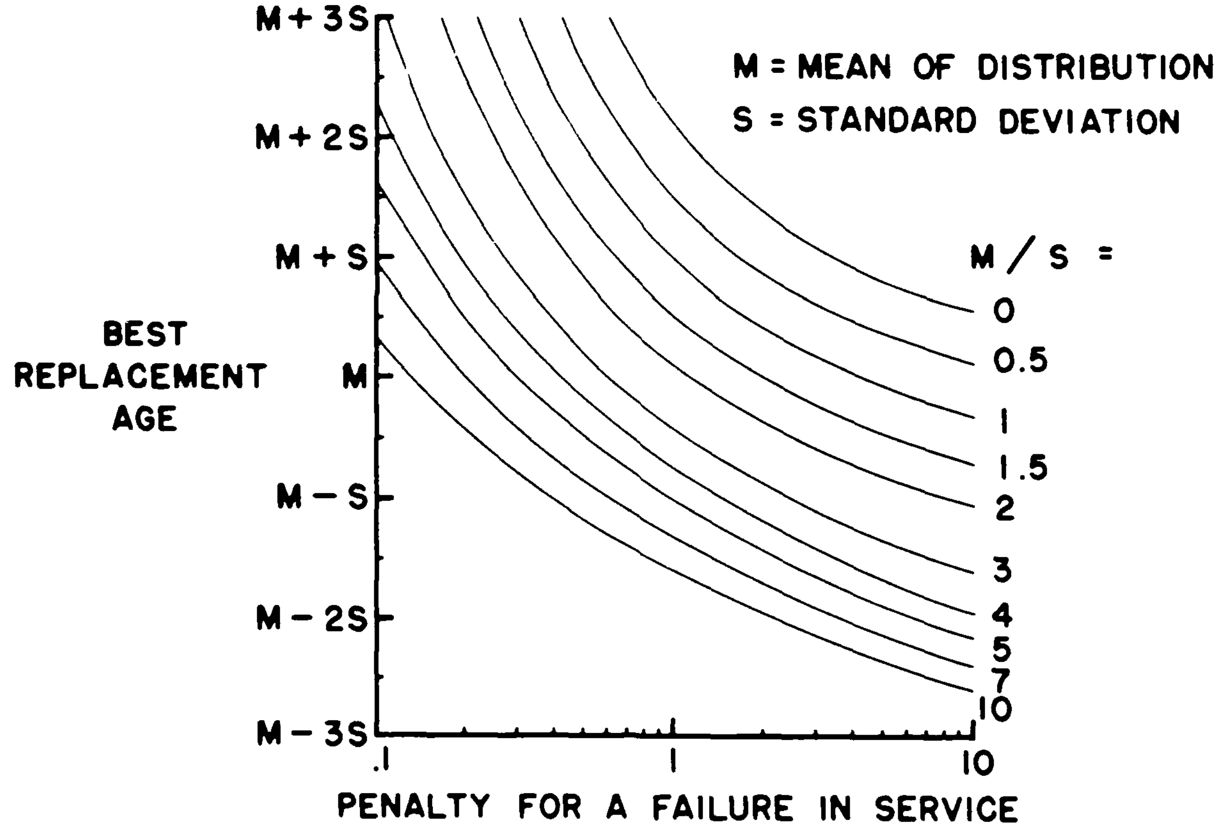


Fig. 11

CAUTION AREAS

- POTENTIAL LOSSES
- COST OF ADMINISTRATION
- ◉ CONFIDENCE IN ESTIMATES
- ◉ RELIABILITY GROWTH
- ◉ DECISION TO EXTEND
- ⊛ PHASE-OUT

Fig. 12

This next group is not as easy to handle. Since the estimation of failure rates is necessarily inexact, some attention must be given to the possibility that the failure characteristics may be somewhat different from what we think they are. As time passes, we generally accumulate more failure experience and this problem subsides. However, a new one comes along to take its place: this is the growth in reliability which we hope will accompany product-improvement programs. A planned-replacement program should reflect the current failure-rate experience. As reliability improves, the desirable replacement age may move upward into a region where we may have little or no failure experience. It's necessary then to exercise some caution in the decision to extend the mandatory replacement age, and Research Memorandum RM-2810*, of which the present study is an abbreviated version, gives considerable attention to this problem.

The rules for determining the best time for planned replacement were developed on a long-term-average basis. During phase-out of a system, a somewhat different policy can be beneficial, one which has been developed by mathematicians at Sylvania's Electronic Defense Laboratories and is referenced in RM-2810-PR.

Briefly, the results and conclusions of the study are these (Fig. 13):

In order to be at least potentially worthwhile, planned replacement has two prerequisites: an increasing failure rate, or wearout characteristic, and some penalty associated with a failure in service. If either one of these is missing, the best policy is replacement at failure only. A substantial number of parts in Air Force Weapon Systems fail to meet these requirements.

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*M. Kamins and J. J. McCall, Jr., Rules for Planned Replacement of Aircraft and Missile Parts, The RAND Corporation, Research Memorandum RM-2810-PR, November, 1961.

RESULTS AND CONCLUSIONS

WORTHWHILE PLANNED REPLACEMENT REQUIRES

- INCREASING FAILURE RATE (WEAROUT) *AND*
- PENALTY FOR FAILURE IN SERVICE

REPAIR OF A FAILURE

- EXTRA TIME
- EXTRA RESOURCES

ANALYSIS OF FAILURES

- RANDOM; REPLACE ONLY AT FAILURE
- CONTINUOUS DISTRIBUTIONS; NOMOGRAM
- DISCRETE DISTRIBUTIONS; COMPUTING ROUTINE

PLANNED REPLACEMENT MAY YIELD BENEFITS

- MISAPPLICATION CAUSES NEEDLESS EXPENSE

Fig. 13

The repair of a failure in service typically involves more time and resources than does a planned replacement. We saw an example in the case of airline operations.

The analysis of failure characteristics of aircraft parts shows that a substantial number have a constant failure rate -- so-called random failures. These parts should be replaced only at failure, at least until they show some demonstrable wearout in later life. Another group of parts has failure characteristics which can be represented well by some of the continuous probability distributions of mathematical statistics. We have provided nomograms showing optimum replacement policies for four such families of distributions. Most parts have failure characteristics which can be described only by discrete, or piece-by-piece distributions. We have developed a computing routine for determining optimum policies for these parts. Many parts in the latter two categories do display wearout, and are potential candidates for planned replacement.

Planned replacement as a concept carries no guarantee of benefits. However, we have developed tools which show when and to what extent gross benefits can be expected. These should then be weighed against the effort and expense that the management of a planned-replacement program entails.

When planned replacement is improperly applied -- to parts with random failures, for example -- it will cause substantial unnecessary expenditures of maintenance manpower, spare parts, and weapon-system downtime. Eliminating these misapplications can yield substantial payoffs.

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